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HOLOGRAPHIC FLOW VISUALIZATION WITHIN A ROTATING COMPRESSOR BLADE ROW

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Copies of nine selected holograms are available on loan.

16. Abstract

Rapid double-pulsed holographic techniques were used to visualize the shock configurations in the tip region of a lightly loaded, high tip speed (488 m/sec) fan stage. These holograms showed the passage shock emanating from the blade leading edge, a moderately strong conical shock originating at the intersection of the part span shroud leading edge and the blade suction surface, and a second conical shock originating at the intersection of the part span shroud and the blade pressure surface. Due to a limited viewing angle, the bow waves upstream of the rotor could not be observed, and only limited details of the trailing edge shocks were obtained. The results of these studies appear extremely promising. Reasonable details of the shock patterns were obtained from holograms which were made without extensive rig modifications. These studies indicated several advancements that would give even better results. Larger viewing windows and holographic plates would permit a wider viewing angle and give much more coverage of the regions of interest. Shorter time delay for double-pulsed holograms is also desirable. This would minimize blade movement and give clearer holograms. With these improvements of technique effective visualization of shock configurations, at least outboard of part span shrouds, should be possible.

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INTRODUCTION

In order to increase stage pressure ratios, modern turbofan and turbojet engines utilize transonic stages in which the flow velocity relative to the rotor blades is supersonic over a large part of the blade span. Shock waves occur on those portions of the blade where the inlet relative flow is supersonic. To minimize the losses associated with these shocks, it is essential that weak oblique-type shocks be maintained as opposed to strong normal type shocks. Due to the radial variations of blade inlet angles and relative velocities, the existing shock waves are highly three-dimensional whereas design procedures are basically two-dimensional. Therefore, the shocks are not precisely defined in the design process. Understanding of the performance of such transonic stages can be improved if a clear definition of the three-dimensional shock patterns can be achieved.

High response pressure transducers have been used to obtain data on flow fields ahead of, behind, and over the tips of transonic rotors. However, the severe centrifugal force fields existing in high tip speed transonic rotors have prevented attainment of successful flow measurements within the passages between blades in actual rotating blade rows. These latter data are most significant in defining flow conditions within the blade passages. Holography indicated promise as a means of visualizing the location of the three dimensional shock patterns. Therefore, NASA awarded two contracts to study the applications of holography to flow visualization in high speed transonic rotors. The results of these studies are given in references 1, 2, and 3.

Both of these programs used rapid double pulsed ruby laser holographic approaches. The first program, reference 1, used a reflected light approach which in practice had a very limited field of view. The second program, reference 2, used a transmitted light approach which was somewhat more complicated to apply, but gave a larger field of view for the blade tip region. Copies have been made of nine selected holograms from the second program. A set of these copies can be obtained on a loan basis. A form and directions for requesting the loan of a set of these holograms is included in the front portion of this report.

This report briefly outlines the apparatus and test procedure for making the holograms, presents the performance of the test compressor, indicates the operating conditions for which holograms were made, and discusses

the results obtained from the holographic study.

APPARATUS AND PROCEDURE

Details of the rotor design used in this program were as follows:

Tip speed, m/sec	488.6
Tip diameter, m	0.73
Specific flow, kg/m^2sec	205.1
Corrected flow, kg/sec	67.09
Rotor inlet hub-tip ratio	0.5
Stage pressure ratio	1.5
Number of rotor blades	40
Rotor tip solidity	1.622

This rotor design used weak oblique shocks in the high Mach number tip region to minimize losses. A schematic of the blade sections in the tip region is given in figure 1. The dotted lines represent the effective blade surface, and the solid lines the actual blade surface as obtained by application of boundary layer displacement thickness corrections. From A to B the effective surface follows a free streamline. Point B is the emanation point of the first captured Mach wave. From B to C, the effective suction surface follows a free streamline. Point C is the intersection of the weak oblique leading edge shock and the suction surface. The effective surface at point C bends sufficiently to cancel the weak oblique shock and prevent any reflected shocks or expansions. From C to D the effective surface follows a free streamline. A second weak oblique shock enamates from the trailing edge, point D, and is cancelled on the pressure surface at point E. The sharp corners at C and E are rounded slightly on the actual blade to improve off design operation. The pressure surface from A to E is defined by a third degree polynomial, and from E to D it is defined by a free streamline. The rotor blades had a part span shroud at 70 percent span from the hub. The design relative discharge flow was just sonic at the span-wise location of the shroud. A complete description of the aerodynamic and mechanical design is given in reference 4 and Appendix A of reference 5.

The holographic approach used to generate the holograms discussed in this report employed a system whereby diffuse laser light was transmitted diagonally across the inlet as shown schematically in figure 2. Light enters the test fan through the large window ahead of the rotor inlet, passes by the centerbody, through the blade tip region, and out through the window over the blade tip onto the holographic plate. To make the holograms for this study, the fan operating condition was set and the laser pulsed twice at a time interval on the order of 5 microseconds. Details of this holographic system, its installation, and operating techniques are given in reference 2.

RESULTS

The performance of the stage used for this holographic study is given in figure 3. At design speed and pressure ratio, the flow was 4 percent above the design value. The stage efficiency at design speed and pressure ratio was 81 percent. The peak stage efficiency at design speed was 84 percent. Peak efficiency at 95 percent speed was slightly over 85 percent, but at 90 percent speed the peak efficiency dropped to 83 percent and then increased as speed was decreased below 90 percent of design speed. The increase in peak efficiency at 95 percent speed is due to the change in shock configurations associated with the starting of supersonic flow in the rotor blade tip region.

Holograms were taken for the conditions indicated on figure 3 by the symbols. The set of holograms which can be obtained on loan consists of one hologram for each point indicated plus a duplicate for the 1.67 pressure ratio point at 100 percent speed.

Several techniques were used to analyze the resultant holograms. These included (1) mounting the hologram in a laser light system and photographing the image through the hologram, (2) mounting a photographic plate in the image field, and (3) simply viewing the image field by eye. The latter scheme proved most effective when an actual set of blades was mounted in the image field and the magnification of the image was set to match the blade scale. A photograph of the blades in the image field is shown in figure 4. By placing wires on the observed shock planes in the model blades in the image plane, the location of specific shock planes can be defined. Viewing from several angles and using holograms with the blades in various positions with respect to the viewing window aided materially in defining the shock plane locations. After the shock planes were completely defined by the system of wires, a model was made using sheets of transparent plastic to define the various shock planes.

Figure 5 shows two views of the blade model with shock waves for a 100 percent corrected speed operating point and a pressure ratio near design. The holographic viewing angle for these tests was too small to permit observations of the bow waves forward of the blade leading edge. Therefore, only shocks within the actual blade passage are shown. This model also shows a tip leakage vortex along the suction surface at the tip. This tip leakage vortex tends to obscure shock definition near the suction surface in the tip region. There is a rather weak oblique shock starting from the blade leading edge and terminating on the suction surface near the blade trailing edge. This shock is similar to the forward passage shock specified in the design, but appears to be nearly normal to the blade at the suction surface. The design assumed that this shock was always oblique. This deviation from design intent may be due to blade boundary layer effects or to effects of the tip leakage vortex.

Another shock wave, identified in figure 5 as first shroud shock, starts at the leading edge of the part span shroud and extends from blade to blade. It is swept back in the flow direction and intersects the outer wall near the blade trailing edge. The exact leading edge of this shock at various positions across the passage cannot be determined due to a limited viewing angle, but this appears to be a somewhat conical-shaped shock emanating from the shroud leading edge on the blade suction surface. On the pressure surface and at other positions across the blade passage, this first shroud shock is ahead of the shroud leading edge. Further back in the passage a second shock is observed which appears to emanate in the region of the intersection of the part span shroud and the pressure surface of the blade. This second shroud shock very nearly coincides with the passage shock near the blade trailing edge. These part span shroud shocks obviously affect the flow in the passage in the tip region, but were not considered in the design of the blades.

A blade trailing edge shock was also observed. This trailing edge shock was represented on the model with a clear plastic sheet and, therefore, is not visible in the picture shown in figure 5. This trailing edge shock appears to sweep forward at smaller radii, and becomes a nearly normal shock as the stage is throttled toward stall. Because of the limited viewing angle, definition of this trailing edge shock is not as positive as those in the forward part of the passage.

Figure 6 is a photograph of a hologram for a 90 percent speed mid-flow range point. From this view, it can be seen that at this speed the passage is not started in the tip region and the forward passage shock is a strong normal shock. This strong normal shock probably accounts for the dip in peak efficiency which is shown on figure 3 for 90 percent speed.

There was a remarkable consistency of shock patterns for different holograms for a given operating condition. This was not expected because other studies in which hot wire measurements of blade wakes and high response pressure transducer measurement of pressures over the rotor blade tips indicated large variations from blade to blade and from revolution-to-revolution for the same blade. The shock patterns from holograms taken on two completely separate runs, however, showed very good agreement.

More details on the results of this program are given in reference 2. In general excellent results were obtained from the rapid double pulsed holograms insofar as shock locations for the forward part of the passage are concerned. Details ahead of the blade row and in the trailing edge region were not so well defined. Several things could be done to improve the quality and viewing area for the type of holograms discussed herein. Most important would be to increase window and hologram plate size. The present study was done with a 7.6 by 12.7 cm viewing window and 10.2 by 12.7 cm (4 x 5 in.) holographic plates. Use of much larger windows and larger holographic plates would increase the field of view and permit better evaluation of conditions in the leading and trailing edge regions of the

blades. Shorter pulse separation times would reduce blade movement and provide clearer holograms.

CONCLUDING REMARKS

Rapid double pulsed holographic techniques were used to visualize the shock configurations in the tip region of a lightly loaded, high tip speed (488 m/sec) fan stage. These holograms showed a passage shock emanating from the blade leading edge, a moderately strong conical shock originating at the intersection of the part span shroud leading edge and the blade suction surface, and a second conical shock originating at the intersection of the part span shroud and the blade pressure surface. Due to a limited viewing angle, the bow waves upstream of the rotor could not be observed, and only limited details of the trailing edge shocks were obtained. The results of these studies appear extremely promising. Reasonable details of the shock patterns were obtained from holograms which were made without extensive rig modifications. These studies indicated several advancements that would give even better results. Larger viewing windows and holographic plates would permit a wider viewing angle and give much more coverage of the regions of interest. Shorter time delay for double-pulsed holograms is also desirable. This would minimize blade movement and give clearer holograms. With these improvements of technique more effective and meaningful visualization of shock configurations, at least outboard of part span shrouds, should be possible.

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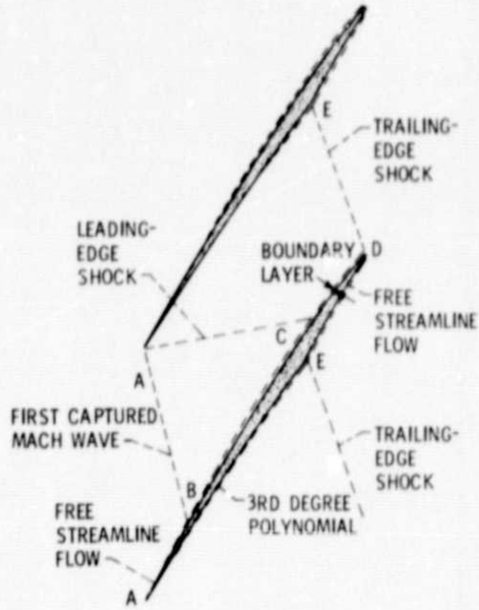

Figure 1. - Representative rotor blade section (483.6 m/sec rotor).

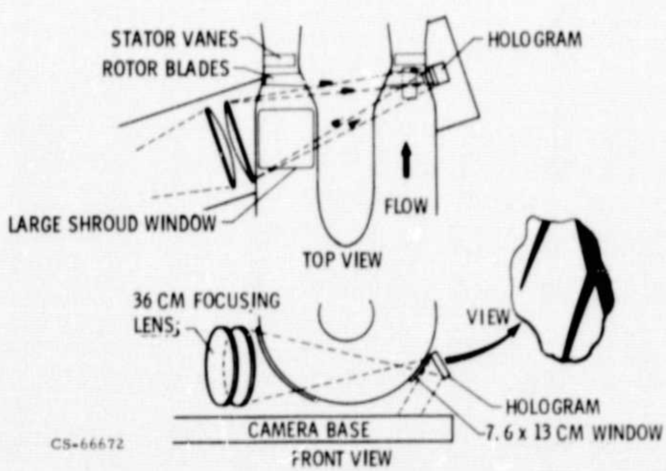

Figure 2. - Optical paths for transmitted light holography.

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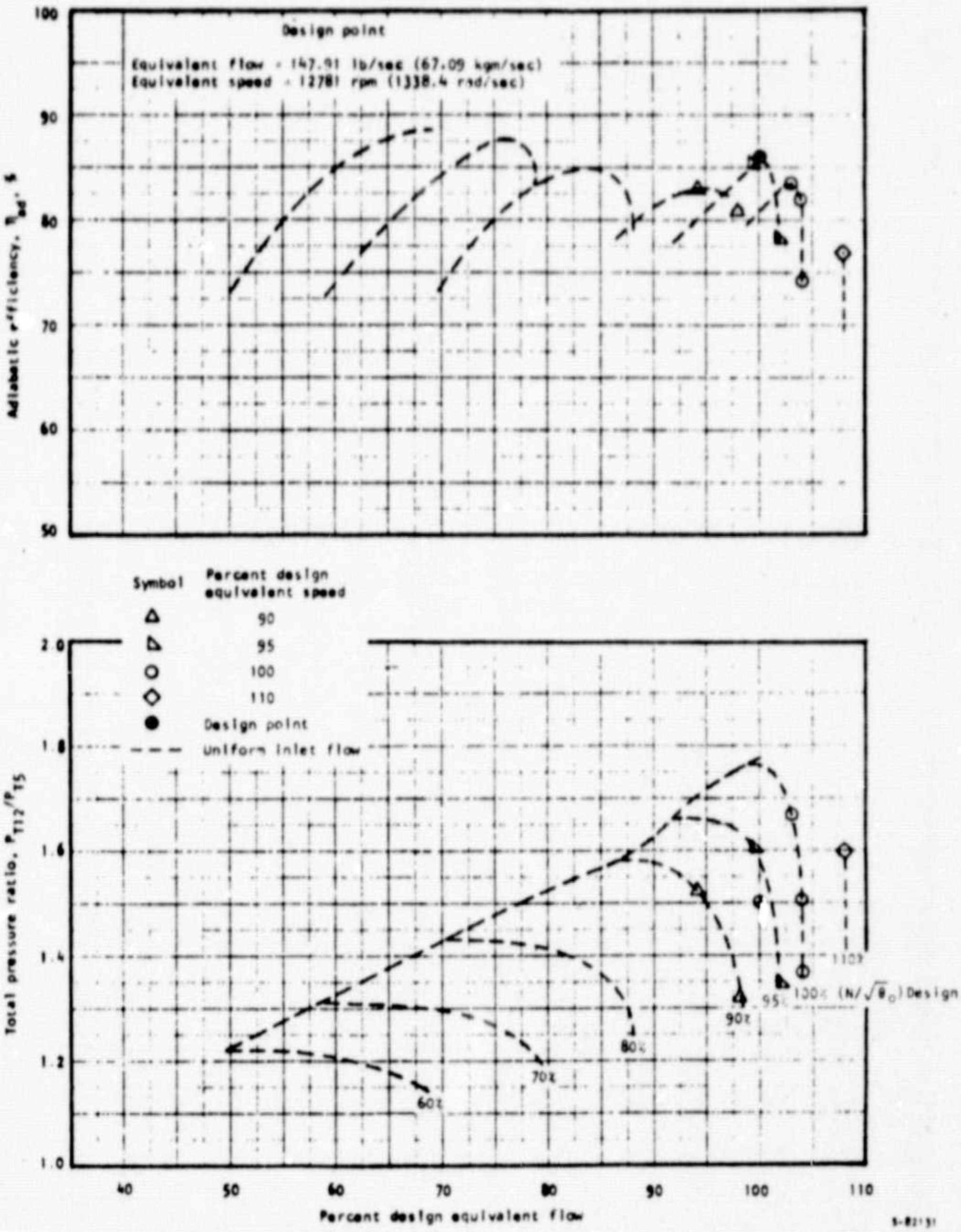

Figure 3. --Flow Visualization Data Points Superimposed on Overall Stage Performance Map.

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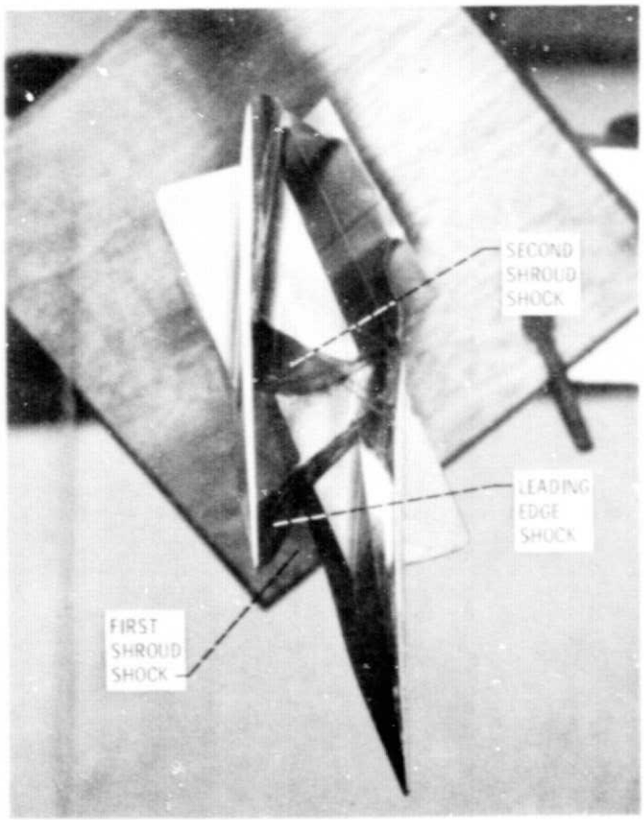
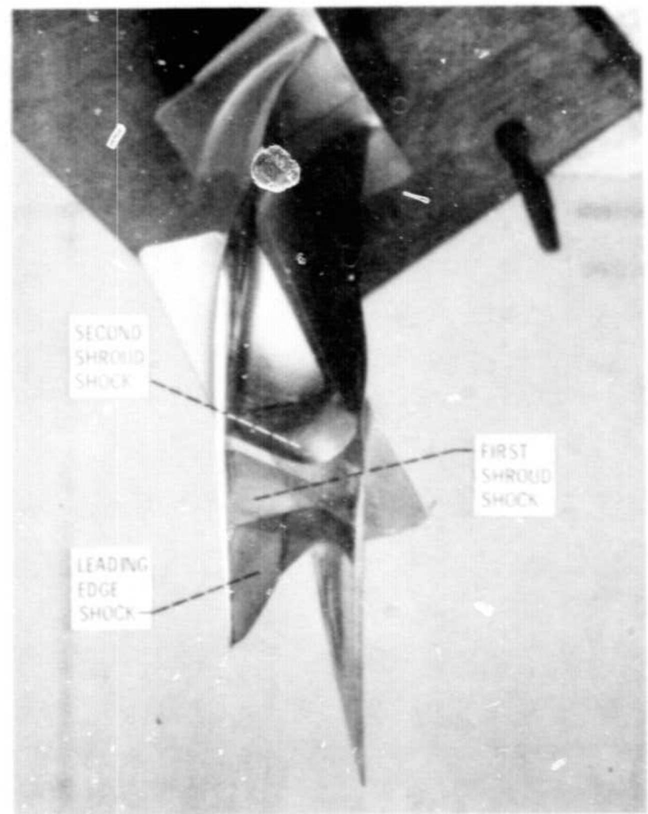
Figure 4. - View of transmitted light hologram image coincident with rotor blades.



(a) TOP VIEW.



(b) REAR VIEW.

Figure 5. - Views of 488.6 m/sec rotor blade model with shock system at design speed and near design pressure ratio.

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Figure 6. - View of transmitted light hologram for 90 percent speed.